

Physical-Biological-Optics Model Development and Simulation for the Pacific Ocean and Monterey Bay, California

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LONG-TERM GOALS

Modeling and predicting ocean optical properties requires linking optical properties with the physical, chemical, and biological processes in the upper ocean. Our long-term goal is to incorporate optical processes into coupled physical-biological models for both open ocean and coastal waters, develop and improve integrated ocean forecasting systems, including prediction of ocean optical properties.

OBJECTIVES

- 1) To improve performance of the coupled physical-biological model, which is based on the Navy Coastal Ocean Model (NCOM) for the California Current System and Regional Ocean Model System (ROMS) for the Pacific Ocean;
- 2) To incorporate optical variables into the improved coupled 3D physical-biological model for the Pacific Ocean and California Current System;
- 3) To evaluate physical-biological-optical models with remote sensing and available in situ observations;
- 4) To use these variables to drive a radiative transfer model (EcoLight) that simulates and predicts the subsurface light field as well as the ocean surface optical measurements.

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APPROACH

To achieve the first objective, we have conducted a series of 3D physical-biological model simulations for the Pacific Ocean and California Current System to test the model performance. By collaborating with the Dynamics of Coupled Processes Section (led by Dr. Igor Shulman) at NRL, we have incorporated the Carbon, Silicate, and Nitrogen Ecosystem (CoSiNE) model into both the Navy Coastal Ocean Model (NCOM) and Regional Ocean Model System (ROMS). The CoSiNE model (Chai et al., 2002; 2003; 2007; and 2009) was developed originally for the equatorial and Pacific Ocean. During the past several years, we have implemented the CoSiNE model and improved the performance. We have successfully transferred the updated CoSiNE model into a biogeochemical module, which could be easily incorporated into other numerical models.

To achieve the second and the forth objectives, we incorporate spectrally-resolved inherent optical properties (IOPs) into the existing ROMS-CoSiNE model. To simulate IOPs realistically in the biological model, we have modified the CoSiNE model by incorporating phytoplankton carbon, nitrogen, and chlorophyll as separate state variables. Modeled phytoplankton chlorophyll can be compared with satellite derived chlorophyll and absorption coefficients, and phytoplankton carbon can be compared with satellite derived backscattering coefficients. Because CDOM plays an important role in absorption spectra in the ocean, we also include a microbial loop, including the color dissolved organic carbon (CDOC) in the modified CoSiNE model to mimic color dissolved organic matter (CDOM) dynamics in the ocean which was treated as a constant value in previous one-dimensional model (Fujii et al., 2007). The modeled CDOC concentration is converted to CDOM absorption coefficient through an empirical relationship (Bissett et al., 2004) and further compared with satellite data. By doing so, more model variables are compared and constrained by the satellite data. With the modeled phytoplankton carbon, chlorophyll and CDOC concentration, spectrally-resolved IOPs such as phytoplankton absorption, CDOM absorption and particulate organic carbon concentration (POC) backscattering coefficients are then calculated with the prescribed specific spectra for absorption and backscattering. These IOPs are used as an optical feedback to drive the vertical distribution of underwater light field that can substantially affect phytoplankton photosynthesis and shortwave radiation near the surface. To achieve this, two radiative transfer schemes are used here. The first one is a simplified and empirical scheme that estimates underwater light attenuation from IOPs (Penta et al., 2008). This scheme is computationally cheap and easy to apply in large-scale physical-biogeochemical simulations. We also collaborate with Dr. Curt Mobley at Sequoia Scientific for the second scheme to implement the updated version of EcoLight into the ROMS-CoSiNE model for application to the Pacific Ocean and California Current System. The updated EcoLight will simulate detailed and spectrally-resolved underwater light field instead of only light attenuation, which not only can simulate optical feedbacks to biological activities but also can simulate biological feedbacks to ocean temperatures.

To achieve the third objective, the performances of the coupled ROMS-CoSINE-Optics model are evaluated by comparing the model results with SeaWiFS and MODIS satellite data and available in-situ measurements. There are a lot of algorithms being used to calculate ocean optical properties from satellite data. What we used for the model-satellite data comparison is the one called quasi-analytical algorithm (QAA) (Lee et al., 2002), which is a promising algorithm for deriving inherent optical properties from ocean color. In-situ measurements including SeaWiFS Bio-optical Archive and Storage System (SeaBASS) dataset, CalCOFI measurements (<http://calcofi.org/>) and World Ocean Atlas 2005 (WOA05) are also used to evaluate model's performance.

WORK COMPLETED

We have fully evaluated the original 3D ROMS-CoSiNE model performance for the Pacific Ocean and compared the model results with available in-situ observations. These evaluation activities comprehensively include carbon cycles (Chai et al., 2009), ecosystem productivities (Liu and Chai, 2009a), biological responses to physical environment (Liu and Chai, 2009b), and meso-scale eddy activities (Xiu et al., 2010), as well as the biogeochemical responses to the meso-scale eddies (Xiu and Chai, 2011; Xiu et al., 2011).

We incorporated a bio-optical module and the original CoSiNE code into the Navy Coastal Ocean Model (NCOM) for the California Current System, and have been coordinating effort to improve the CoSiNE performance in the NCOM.

We modified the CoSiNE code by incorporating optical variables and feedbacks in the ecosystem model and coupled it in the ROMS-CoSiNE-Optics model for the Pacific domain.

We evaluated the ROMS-CoSiNE-Optics model results with remote sensing derived IOPs and other biological parameters for the Pacific Ocean and CalCOFI region.

We have collaborated with Dr. Curt Mobley to incorporate EcoLight into an idealized ROMS-CoSiNE model for an upwelling system. EcoLight was completely rewritten from scratch in Fortran 95 by Dr. Curt Mobley to bring it up to the standards of the ROMS-CoSiNE code. Some initial results have been reported as an invited talk at the Gordon Research Conference in June 2011 by Dr. Chai.

RESULTS

We have conducted a series of the ROMS-CoSiNE model, without the optical component, for the Pacific Ocean for the period of 1990 to 2008. For doing so, we can evaluate the ROMS-CoSiNE model results with available observations, and then improve the CoSiNE model performance (Liu and Chai, 2009a; Liu and Chai, 2009b; Bidigare et al., 2009; Chai et al., 2009; Xiu et al., 2010; Palacz et al., 2011; Xiu and Chai, 2011; Xiu et al., 2011). Since these ROMS-CoSiNE model results have been published in the peer-reviewed journals, we are not including these results in this report.

The original 10-component CoSiNE model from Chai et al. (2002) was modified to include 27 state variables (Figure 1). With these new variables, the model can simulate photosynthesis, inorganic nitrogen assimilation, and pigment synthesis processes separately associated with dynamic carbon-to-chlorophyll and carbon-to-nitrogen ratios. This separation allows the decoupling between modeled phytoplankton carbon and chlorophyll, and corresponding optical absorption and backscattering, respectively, which was observed from satellite studies (e.g., Behrenfeld et al., 2005). The carbon and nitrogen cycling system was also realistically improved by adding the dissolved pool and bacterial dynamics in the model. CDOC modeled as a colored byproduct of dissolved organic carbon (DOC) is split into labile (L_{doc}) and semi-labile (S_{doc}) pools according to their turnover rates. In the model, CDOC is produced by phytoplankton mortality, zooplankton messy feeding and mortality, and detritus breakdown. It is consumed by bacteria through the whole water column, and photobleached by UV light in the upper water layer. The subsequent bacterial respiration and photobleached CDOC both can contribute to the budget of total CO_2 (TCO_2) and further affect carbon cycling in the ocean.

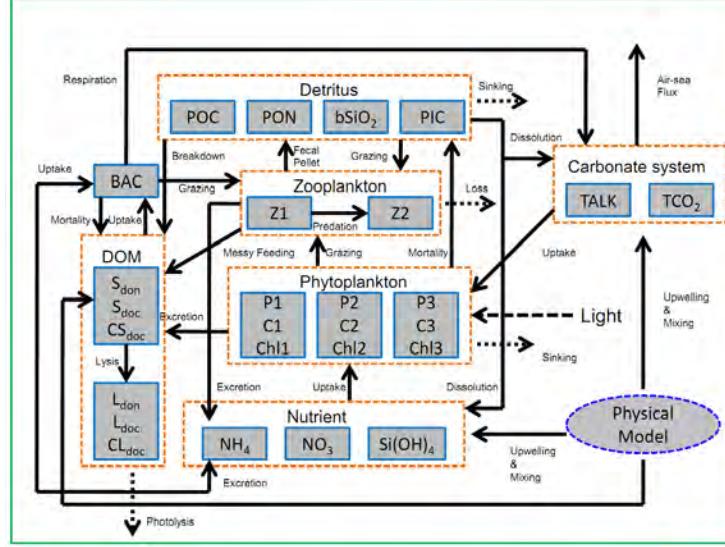


Figure 1: The flow-chart of modified CoSiNE model.

Performances of the coupled ROMS-CoSINE-Optics model are evaluated by comparing the model results with SeaWiFS satellite data. CalCOFI region is chosen as the model evaluation area, where oceanography has been studied extensively for a long history. We compose our 3-day model outputs into monthly products in order to compare with satellite data. For now, the spatial resolution of the coupled model is 50 km. The model is initialized with climatological data and has been forced by realistic wind, air-sea fluxes of heat and freshwater. Figure 2 shows the spatial average of the model outputs in CalCOFI region. On a mean basis, the model successfully captures the temporal variations of physical, biological and associated optical properties. Modeled sea surface temperature (SST) coincides with WOA05 product, suggesting the well-produced physical condition in the model. The modeled biological variables, phytoplankton carbon, chlorophyll and depth-integrated (0-100m) primary production all reasonably reproduce the first-order variability of satellite data, considering that our model is Pacific basin-scale model with a horizontal resolution of 50 km. Modeled CDOM absorption (a_{cdm}) is slightly lower than QAA product, probably because we do not include terrestrial sources of CDOM in the model. Nevertheless, phytoplankton absorption (a_{ph}) and particulate backscattering (b_{bp}) both reproduce the observed features in terms of seasonal and interannual variations.

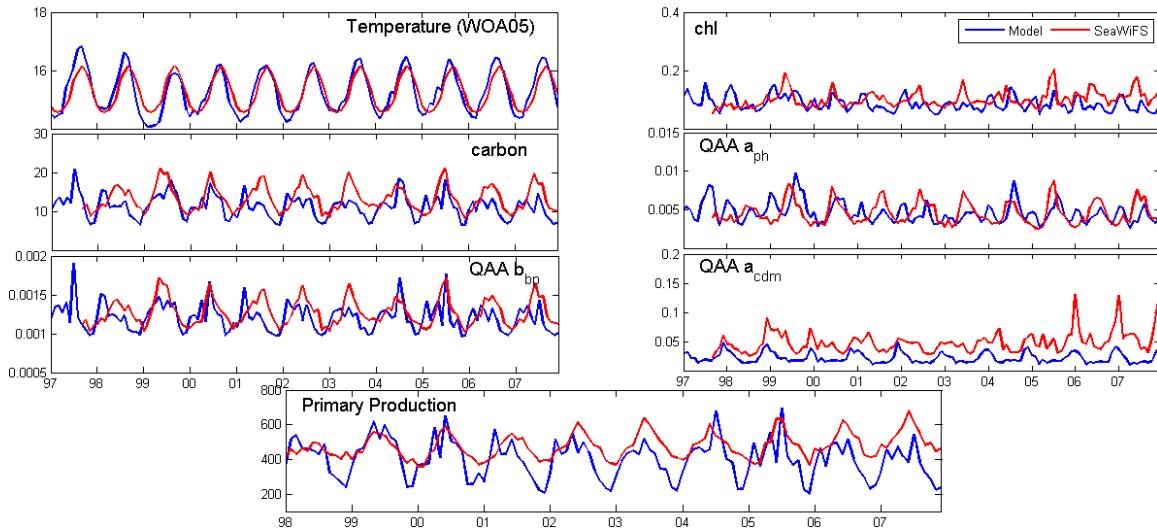


Figure 2: Modeled phytoplankton carbon (mg C m^{-3}), phytoplankton absorption coefficient at 440 nm (m^{-1}), particulate backscattering coefficient at 550 nm (m^{-1}), CDOM absorption coefficient at 410 nm (m^{-1}), and depth-integrated (0-100m) primary production ($\text{mg C m}^{-2} \text{d}^{-1}$). The measurement for temperature is from WOA05 dataset.

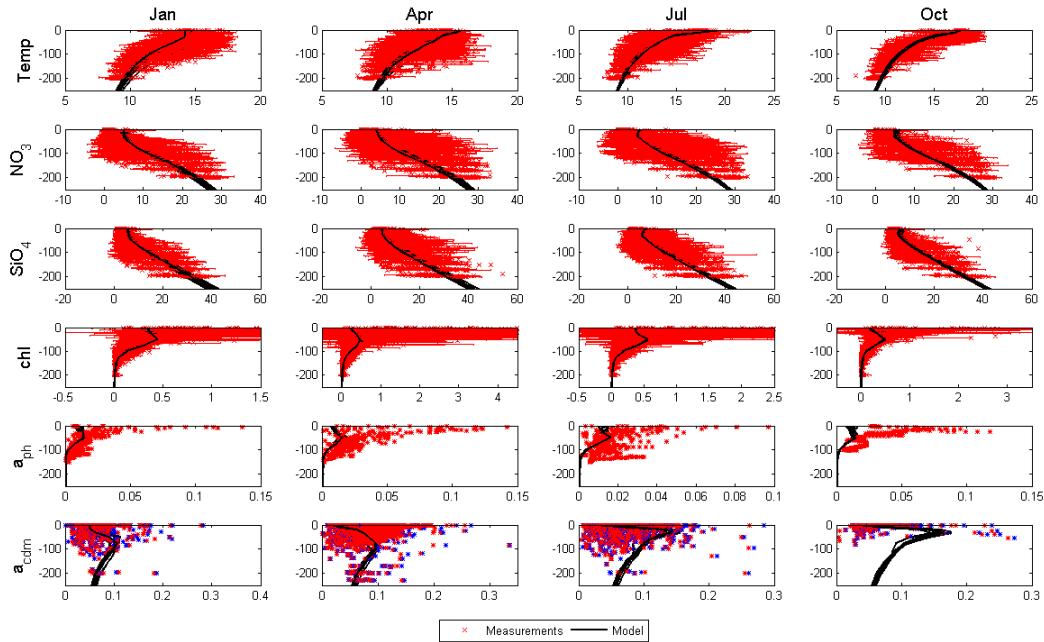


Figure 3: In-situ measurements from the CalCOFI domain. Black curves are the model results during 1992-2009. Temperature ($^{\circ}\text{C}$), $\text{NO}_3(\text{mmol m}^{-3})$, $\text{SiO}_4(\text{mmol m}^{-3})$ and $\text{chl} (\text{mg m}^{-3})$ data come from the CalCOFI website (<http://www.calcofi.org/>). a_{ph} and a_{cdsm} data come from the SeaBASS (<http://seabass.gsfc.nasa.gov/>).

Comparisons of vertical distribution patterns between model and in-situ data are shown in Figure 3. Due to the scarce of in-situ measurements, we cannot provide a point-to-point comparison. Figure 3 shows the comparison between the model and all the available historical datasets in the CalCOFI region. Overall, the model can reproduce the variations of physical, biogeochemical and optical properties in both magnitudes and distribution patterns. The model suggests the low-nutrient and high-nutrient conditions in the surface and deep waters, respectively. Strong subsurface maximum both in chlorophyll and phytoplankton absorption are clear throughout the year. CDOM absorption, differs slightly, showing strong and shallow subsurface maximum in summer months, probably produced due to the intense photobleaching by UV light. Note that all the available in-situ measurements are plotted in this figure, but we only show the domain averaged data from the model. Thus, the good performance of the model is on a mean basis.

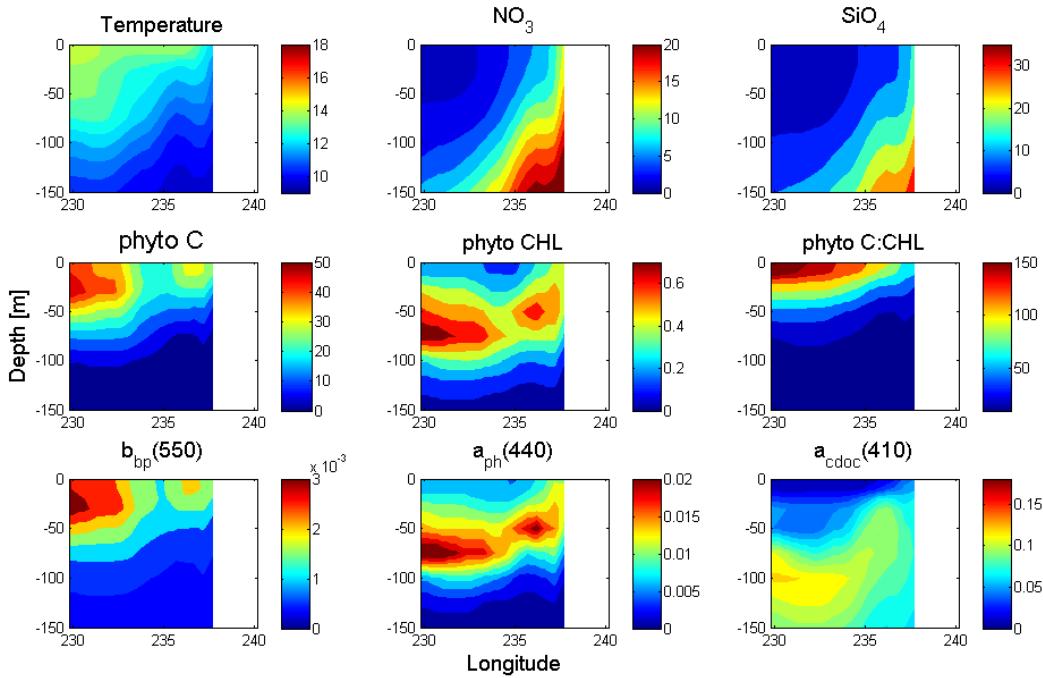


Figure 4: Cross sections of modeled physical, biogeochemical, and optical properties along 36.5N in April averaged during 1992-2009.

Although the model is configured for the Pacific basin with a horizontal resolution of 50 km and some meso- or small- scale structures cannot be resolved, our model is still robust to produce typical coastal features such as the upwelling event. Figure 4 shows a cross section of modeled variables in April. In this period, the coast is dominated by the strong upwelling due to the increased equatorward wind. As shown in Figure 4, cool and nutrient-rich deep waters are brought into the upper layers. Phytoplankton carbon mainly accumulates in the surface layer in response to the photosynthesis. Phytoplankton chlorophyll regulated by both light and nutrients, on the other hand, shows strong subsurface chlorophyll maximum (SCM), and the depth of SCM tends to increase when moving close to the coast as a result of the elevated nutrient condition due to upwelling. Particulate backscattering and phytoplankton absorption show similar patterns to phytoplankton carbon and chlorophyll, respectively. CDOM absorption seems to be influenced by the coastal upwelling stronger than other optical

variables. The depth of subsurface CDOM maximum is about 100 m at 230°E, and it is raised to above 50 m when near the coast.

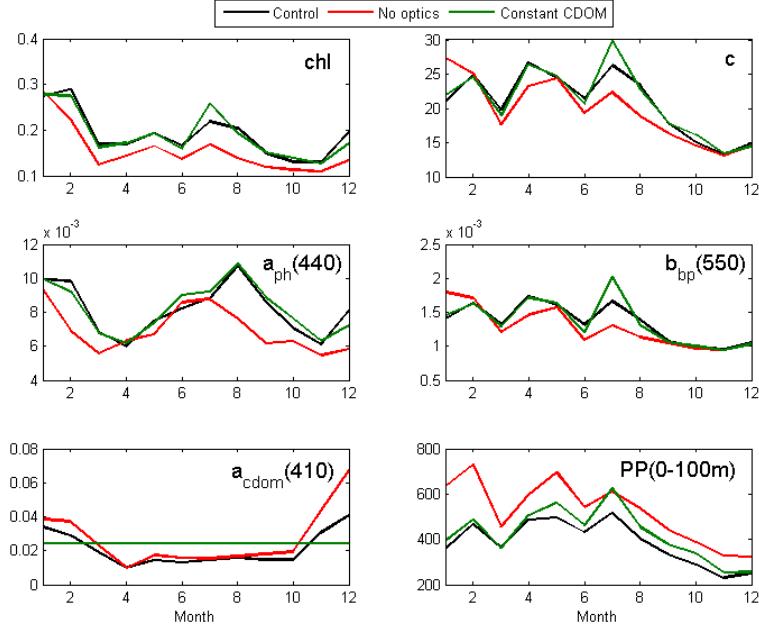


Figure 5: Sensitivity analysis of domain-averaged surface values for 2006 (primary production (PP) is depth-integrated). Control run is the fully coupled model. No optics is the run without optics feedback to the model, and the vertical distribution of photosynthetically active radiation (PAR) was calculated based on phytoplankton biomass only by using an empirical equation (Chai et al., 2002). Constant CDOM is the run similar to Fujii et al. (2007), where optics has feedback to the ecosystem but with a constant CDOM concentration.

In order to illustrate the importance of incorporating optics into the biological model, a sensitivity study was conducted in 2006. Traditional approach (no optics run) in which the vertical distribution of PAR is calculated based on phytoplankton biomass only by using an empirical equation underestimates carbon, chlorophyll, phytoplankton absorption, and particulate backscattering at the surface, but strongly overestimates depth-integrated PP. This is probably caused due to the lack of light attenuation contributed from CDOM. As a result, more light enters into the subsurface layer and stimulates stronger and deeper subsurface maximum than Control run (not shown). Adding an appropriate spatially and vertically constant CDOM concentration in the model (Constant CDOM run) can reduce the discrepancy revealed by the No optics run. Since there is no seasonal variations in the CDOM contribution, PP in the Constant CDOM run compares well with Control run in the early year when CDOM concentration in the whole water column stays low. But during the summer bloom condition when CDOM production peaks following phytoplankton growth, Constant CDOM run tends to overestimate PP compared with the Control run. Note that CDOM concentration at the surface is mainly controlled by UV light, and CDOM over the whole water column is generally controlled by physical and biological processes. In addition, CDOM concentration also varies over spatial scales, we therefore should expect a different CDOM contribution to light attenuation between coastal region and deep oceans.

During the past several months, Dr. Curt Mobley came to UMaine twice (April and July 2011) to work with us on incorporating EcoLight into the ROMS-CoSiNE-Optics model for an idealized upwelling system. We are glad to report that the integrated model system is finally working properly, and producing some really interesting results. Figure 6 shows a comparison between the analytic light treatment (left panels) and EcoLight results (middle panels), the right panels show the difference between these two runs. With EcoLight simulation (everything else are the same as the analytic model runs - physics and biology), during the upwelling period (about three weeks), the EcoLight simulation produce more chlorophyll, by about 0.5 mg/m³ comparing to the analytic light treatment, which is about 10% of the highest value. Interestingly enough that this extra amount of chlorophyll feed back to physical processes, mainly shortwave radiation redistribution near the surface. The EcoLight simulations calculate these processes, but the analytic light treatment does not. So, the temperature difference between these two runs is about 0.5 degree C near the surface (not shown here).

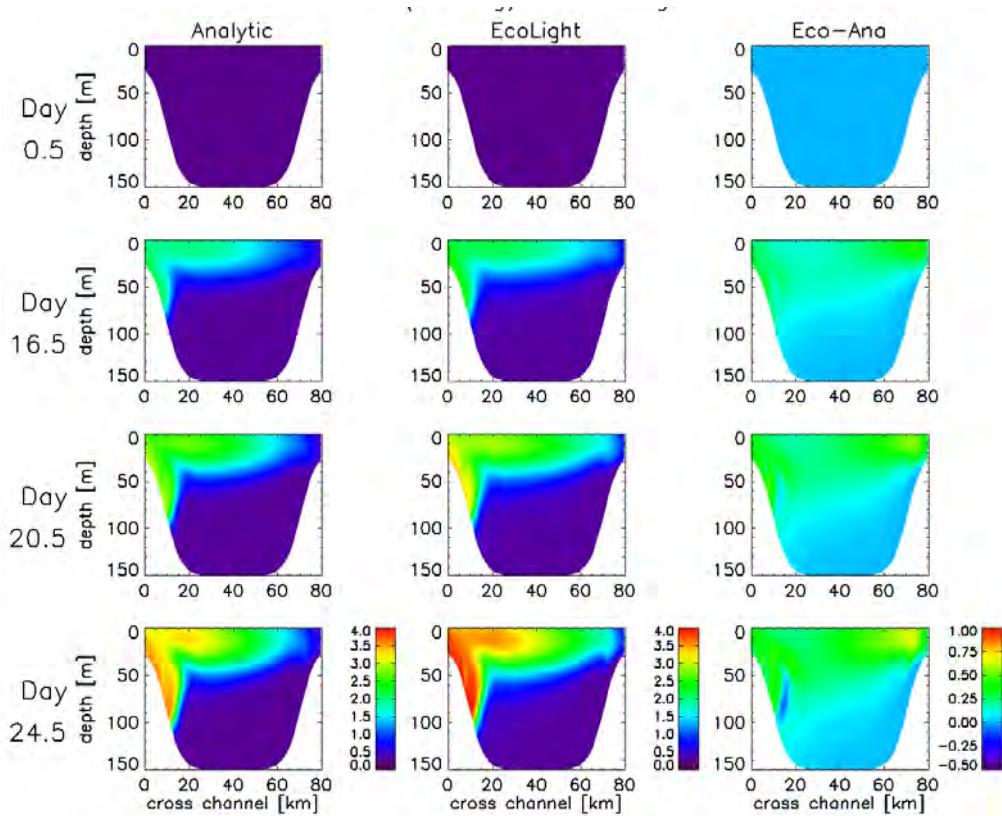


Figure 6: Comparison of modeled chlorophyll between the analytic light treatment (left panels) and EcoLight calculated light (middle panels). The difference between these two light calculations are shown in the right panels. With the EcoLight calculation, the coupled model system produces more chlorophyll.

IMPACT/APPLICATIONS

Incorporating ocean optical processes into coupled physical-biological models enables us to simulate and forecast optical properties in the ocean. To our knowledge, it is the first application of coupled physical, biological, and optical processes to the large-scale simulations. Coupling explicit optics to an ecosystem model provides advantages in generating a more accurate subsurface light field and additional constraints on model parameters that help to reduce model uncertainties. With demonstration of some initial successes of developing physical-biological-optical modeling and data assimilation capability for the Pacific Ocean and California Current System, we should be able to develop an end-to-end ocean forecasting system. Such modeling system would be a powerful tool to design the adaptive sampling strategy and would be an essential component of future field experiments.

RELATED PROJECTS

This project has strong collaboration with other ONR supported projects. Besides working closely with the modeling group at the NRL and their BioSpace project, we are collaborating with Dr. Curtis Mobley of Sequoia Scientific on improving the link between the radiative transfer model (EcoLight) within the ROMS-CoSiNE. We are also collaborating with scientists (Dr. Francisco Chavez) at the Monterey Bay Aquarium Research Institute (MBARI) to use the observational data for the region. Dr. Yi Chao at JPL has been collaborating with us about implementing the CoSiNE model into the ROMS for the Pacific Ocean and the CCS.

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